

Left-handed extraordinary optical transmission through a photonic crystal of subwavelength hole arrays

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Abstract: Metamaterial structures are artificial materials that show unconventional electromagnetic properties such as photonic band-gap, extraordinary optical transmission and left-handed propagation. Up to now, relations of photonic crystals and negative refraction have been shown as well as of photonic crystals and sub-wavelength hole arrays. Here we report a left-handed metamaterial engineered by a combination of sub-wavelength hole array plates periodically stacked to form a photonic crystal structure. It is shown the possibility of fine-tuning the metamaterial in order to permit extraordinary optical transmission and left-handed behaviour. Our work demonstrates the feasibility of engineering left-handed metamaterials by just drilling holes in metallic plates and brings together single structure photonic crystals, extraordinary optical transmission and left-handed behaviour.

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1. Introduction

Three discoveries have altered the state of the art of electromagnetic radiation research over the last years. First, the concept and realisation of photonic band-gap (PBG) structures have opened up new original approaches for the control of light flow and confinement with great technological consequences [1-4]. Photonic Crystals (Ph. C.) are artificial structures which fundamentally inhibit propagation of electromagnetic waves for certain directions and wavelengths [1,3], so-called photonic band-gap (PBG). Artificially introduced defects permit light control and localization [2,4], and for this reason they have been proposed as the photonic counterpart of electronic semiconductors [1].

Second, the demonstration of extraordinary optical transmission (EOT) through sub-wavelength hole arrays and other structures has provided the basis for using subwavelength apertures for a variety of potential applications [5-10]. EOT through subwavelength hole arrays has been explained on the basis of surface plasmons [7-9]. Surface plasmons provide the possibility of localization and the guiding of light in subwavelength metallic structures [7-9], which can be tailored for the creation of plasmonic circuits with the potential ability to merge photonics and electronics [10].

Third, the concept of negative refraction index (NRI) has refreshed the classical electrodynamics field by introducing highly unconventional properties –so-called left-handed metamaterials (LHM)- that can lead to a new class of devices [11-17]. Foremost among these properties is the opposite Snell's refraction law at the interface between a standard and a NRI medium. For NRI to happen, both the permittivity and permeability must be negative simultaneously [11]. Pendry claimed that those NRI materials could act as perfect lenses [12]. Pendry's group had previously shown the feasibility to fabricate an artificial material with negative permittivity using a lattice of thin metal wires [13], and they had also reported how to obtain a negative magnetic response from a lattice of "split rings resonators" [14]. Smith et al. built a structure with simultaneous negative ϵ and μ showing negative refraction for the first time [15]. Since then left-handed metamaterials have been achieved for frequencies in the microwave range [16,17] from split-ring resonators components [14] and their complementary [18]. Only very recently a media with negative permeability at optical frequencies has been reported [19], thus paving the way for NRI materials at visible frequencies [20].

Up to now, relations of photonic crystals and negative refraction have been shown [21,22] as well as of photonic crystals and sub-wavelength hole arrays [23,24] and, moreover, evanescent growth and tunnelling effects have been predicted in paired complementary metamaterials [25,26]. Finally, it has also been suggested that negative refraction and extraordinary transmission through hole arrays are probably different manifestations of the same physical behaviour of surface modes [27].

In this work we show how a left-handed metamaterial can be achieved by the periodic stacking of sub-wavelength hole array plates to form a photonic band-gap structure. Following our previous work in sub-wavelength hole arrays [28-30], a prototype was built and measured in the millimetre wave regime. It is experimentally shown that our structure (Fig. 1) shows both extraordinary transmission and a band-gap, as well as a left-handed behaviour in the frequency band where extraordinary transmission happens (Fig. 2). Further insight is gained by performing theoretical simulations with which the left-handed propagation can be visualised as presented in Figs. 3 and 5 and more explicitly in the provided supplementary video files (Fig. 4).

2. Photonic crystal of subwavelength hole arrays

The metamaterial proposed here consists of a one-dimensional photonic crystal structure made by stacking sub-wavelength hole arrays sandwiched in air as in Fig. 1. It comes up as a natural evolution of Extraordinary Optical Transmission (EOT) structures. This phenomenon appears when $\lambda \approx d$, being d the period of the holes, and when the modes inside the hole are evanescent, i.e., when $d > \lambda_c > a$, being λ_c the cut-off wavelength of the waveguide that forms the hole and a the hole diameter. Each sub-wavelength hole array of our device consists of a perforated aluminium plate with: hole diameter $a = 2.5$ mm, transversal lattice constants $d_x = d_y = d = 5$ mm, cut-off wavelength $\lambda_c = 4.3$ mm ($\lambda_c = 0.85 \cdot d$), metal thickness $w = 0.5$ mm and array dimension of 54×54 holes, very high above the minimum number of holes required for EOT in finite structures [29,30]. With these parameters, EOT appears around 57 GHz ($\lambda = 5.26$ mm) in spite of the fact that the individual holes start to propagate at 70 GHz ($\lambda_c = 4.3$ mm).

The longitudinal lattice d_z between each hole array can be conveniently adjusted in order to select the band gap position of the photonic crystal structure, which is located around a wavelength two times the inter-plate air cavity length. For our experiment, it was selected $d_z = 2.25$ mm, i.e. cavity length $d_z - w = 1.75$ mm, which corresponds to a band-gap centred at 86 GHz ($\lambda = 3.41$ mm). Therefore, the band gap has been placed far away over the frequency band where EOT appears, but close enough to visualize both phenomena within our experimental frequency range (see next section).

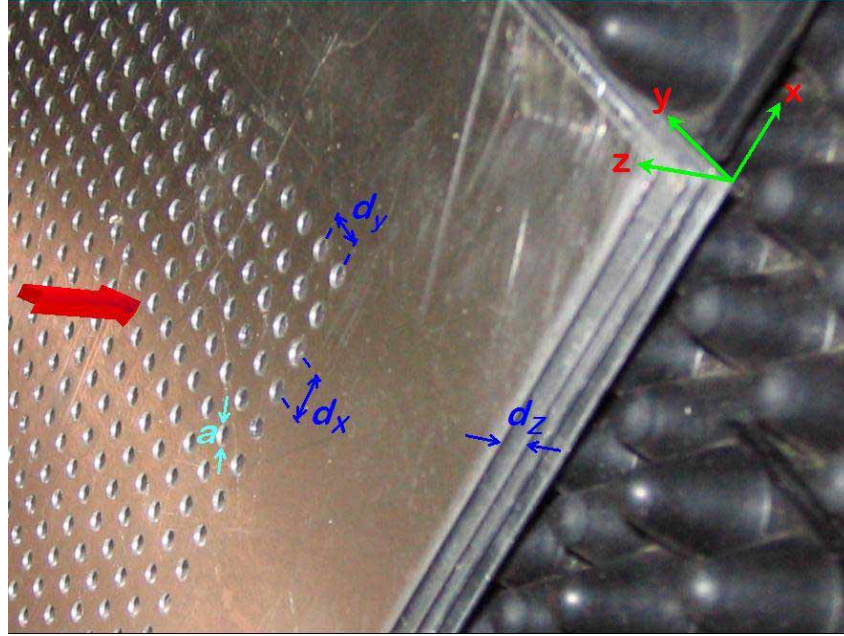


Fig. 1. Picture and dimensions of the photonic crystal made of stacked sub-wavelength metallic hole arrays surrounded of the test bench millimetre wave absorbing material. The number of holes is 54×54 in each plate, being $a = 2.5$ mm, $w = 0.5$ mm, $d_x = d_y = d = 5$ mm, and $d_z = 2.25$ mm.

3. Transmission measurements

Employing an AB MillimetreTM quasi-optical vector network analyzer the amplitude and phase of the transmission coefficient have been measured in the frequency range of 40 up to 110 GHz (2.68 mm up to 7.34 mm) for the structure with the aforementioned parameters.

The normalized amplitude in logarithmic scale, Fig. 2(a), shows a selective enhanced transmission band for a different number of plates, which could be used in various applications [10]. Furthermore, in the band where the transmission reaches its maximum, the phase (Fig. 2(b)) surprisingly increases with the number of structure periods. Note that the phase for 2 plates (black line) is lower than for 3 plates (red line) and this two lower than for 4 plates (blue line) in the EOT frequency range, whereas out of this range the phase behaves normally, i.e. it decreases as the number of plates increases, see also Fig. 2(c). This result reveals that the phase velocity and power flow are in opposite directions in the EOT frequency range and, therefore, left-handed propagation effects appear inside the structure [11].

Practically all the incident power is transmitted to the receiver (see Fig. 2(a)) at the EOT frequency due to a quasi perfect matching between the antennas, the free space and the photonic crystal. This can be made equivalent to a negative index of refraction that is exactly $n = -1$ at some frequency of the first band. A more detailed study of the negative index of refraction, the corresponding permittivity and permeability, as well as the effect of the number of plates and the longitudinal lattice period is under way and will be published elsewhere.

For the case of plane waves at normal incidence, a negative space model can be used for the structure [12]. Oblique incidence simulation and experiments are under development to prove the feasibility to build new refractive devices like flat and parabolic lenses and left-handed prisms [10,12,17]

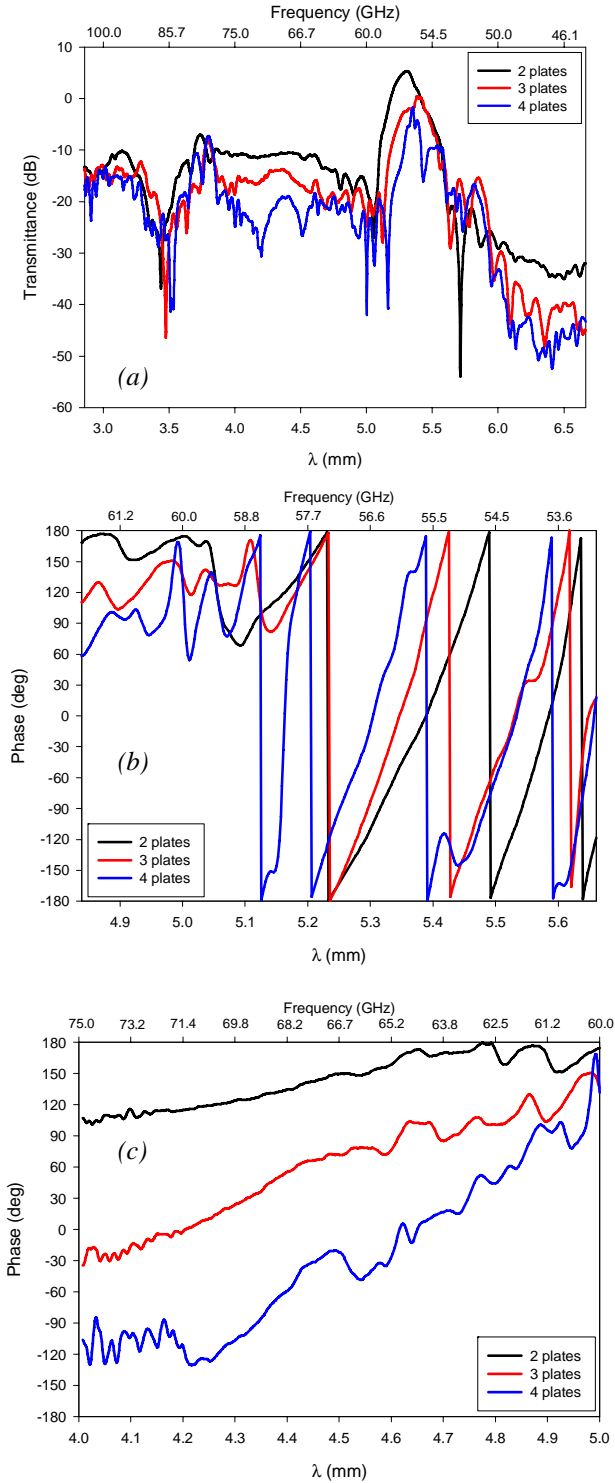


Fig. 2. (a) Measured logarithmic transmission coefficient normalized to the maximum magnitude for $N = 2$ (black), $N = 3$ (red), and $N = 4$ (blue) stacked plates, (b) measured phase varying the number of sub-wavelength hole array plates, $N = 2$ (black), $N = 3$ (red), and $N = 4$ (blue) in the LHM band, and (c) the same as in (b) in the RHM band.

4. Simulation

To gain insight, the full-wave electromagnetic solver CST Microwave StudioTM was employed. Each plate was modelled as an infinite hole array, due to symmetry considerations and computational effort. This code allows us to compute the dispersion diagram and the electric field evolution inside the metamaterial.

The dispersion diagrams for several structures of stacked hole arrays are displayed in Fig. 3. Figure 3(a) shows the dispersion diagram corresponding to the structure with the experimental parameters, i.e., subwavelength holes and $d_z = 2.25$ mm, whereas Fig. 3(b) shows the dispersion diagram for a structure with a longer longitudinal period, $d_z = 2.75$ mm. The EOT for the subwavelength hole array photonic crystal structure corresponds to the first band, which shows a negative slope, i.e., phase velocity opposite to the group velocity, see inset in Fig. 3(a). However, when the longitudinal period is increased, Fig. 3(b), the left-handed behaviour turns into right-handed propagation: now this first band exhibits a positive slope.

In Fig. 3(c), the first band is displayed for structures with shorter longitudinal periods than the operating wavelengths. All the bands have a negative slope showing that the proposed structure effectively works as a left-handed metamaterial. The origin of this behavior will be discussed in the next section.

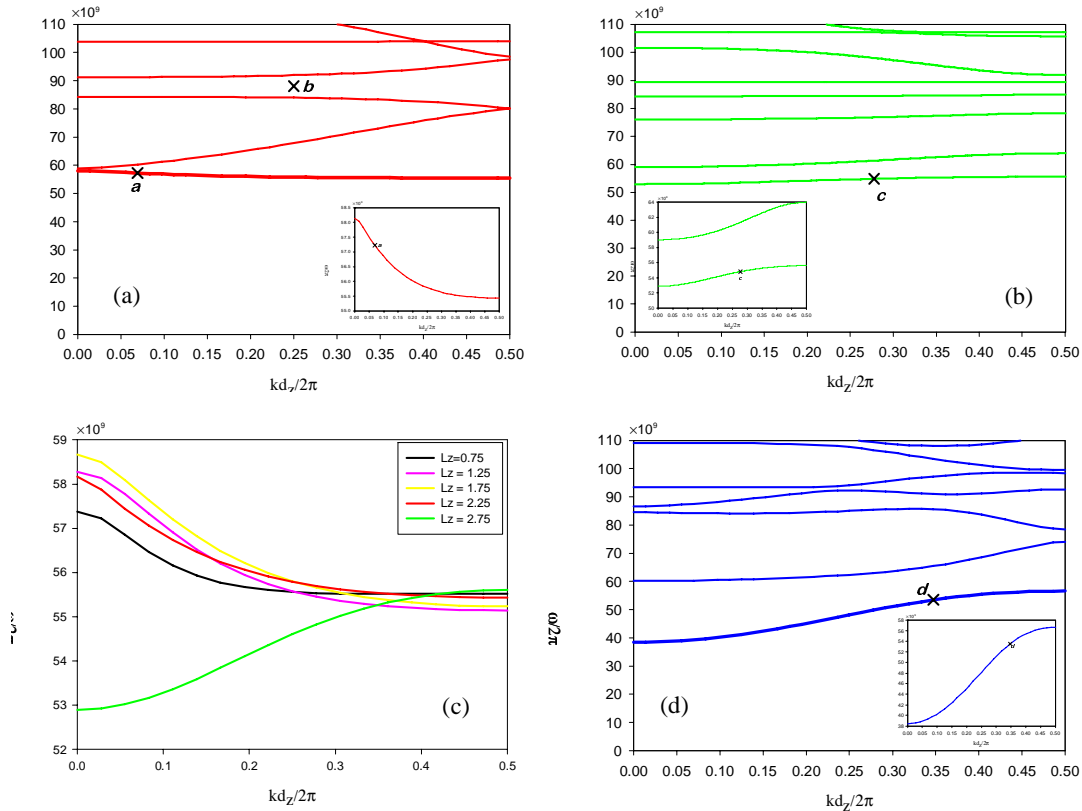


Fig. 3. Simulated dispersion diagrams for photonic crystal made by stacking (a) sub-wavelength hole arrays with $d_z = 2.25$ mm, (b) sub-wavelength hole arrays with $d_z = 2.75$ mm. (c) First band for sub-wavelength hole arrays structures with different longitudinal periods, d_z . (d) Simulated dispersion diagrams for photonic crystal made by stacking propagating hole arrays with $d_z = 2.25$ mm.

In addition, the dispersion diagram for a photonic crystal made of stacked arrays with propagating holes has been also calculated for $d_z = 2.25$ mm (Fig. 3(d)). The parameters of the structure with propagating holes are: $a = 4.0$ mm, cut-off at 40 GHz ($\lambda_c = 7.5$ mm, being $\lambda_c = 1.5 \cdot d$), with the same lattice constants and metal thickness. For the case when the hole arrays are in propagation the first band becomes right-handed (RHM) and the left-handed effect disappears. Note that in both cases, i.e., sub-wavelength and propagating holes, we are dealing with the first band (shown in the insets of Fig. 3). The band gaps are placed at 86 GHz ($\lambda = 3.41$ mm) in both cases due to the same inter-plate cavity. It can be observed that the band-gap in the sub-wavelength case is broader than in the propagating one. Moreover, a previous band-gap is present around 60 GHz ($\lambda = 5$ mm) due to the transversal periodicity related to Wood anomalies [29,30]. Conversely, this band-gap is narrower in the subwavelength case.

A graphical picture of the electric field evolution inside the metamaterial when a plane wave impinges normally to the plates is shown in the supplementary video files. These video files are separately attached for a real-time visualisation of the electric field evolution along different metamaterial structures. Each movie corresponds to the highlighted points (a, b, c and d) in Fig. 3.

For the sub-wavelength structure with $d_z = 2.25$ mm, movie S1 displays the evolution of E_y (vertical component of the electric field) along z direction at a particular frequency inside the first band, say the frequency of maximum transmission with a single plate, 57.3GHz (point a in Fig. 3(a), $\lambda = 5.23$ mm). It can be seen that the phase fronts inside the structure are reversed with respect to the incident and emergent plane wave phase fronts, proving the existence of a backward wave there. In other words, anti-parallel phase and group velocities inside the stacked hole array result in a left-handed metamaterial. For this structure it is also given the electric field evolution at the band gap, specifically at 86 GHz (point b in Fig. 3(a), $\lambda = 3.41$ mm), see movie S2. Note the stationary wave pattern at the face where the plane wave is impinging on.

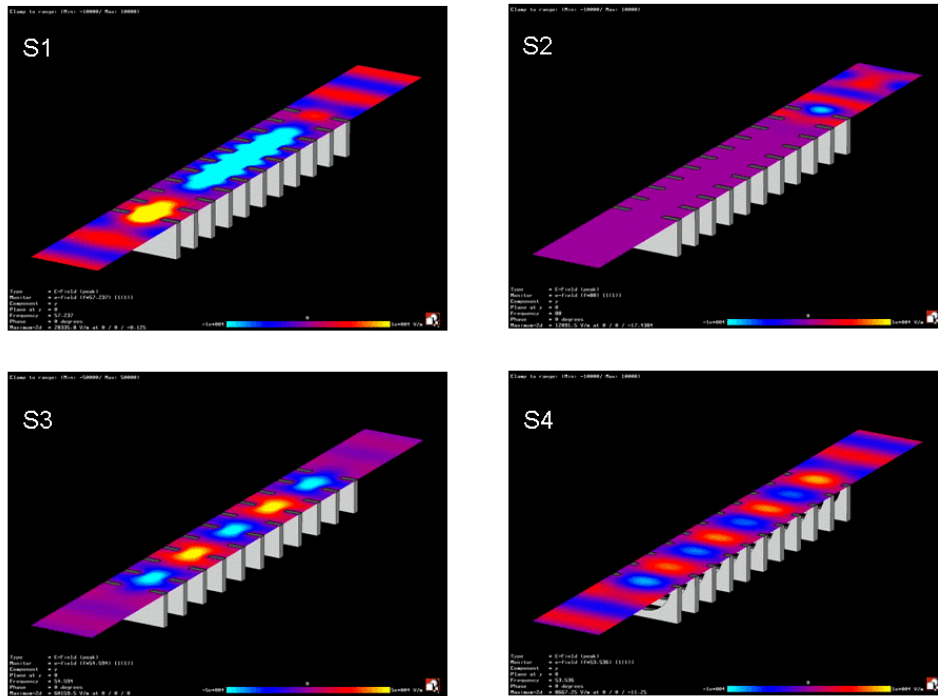


Fig. 4. (600 KB each movie) Movies corresponding to the highlighted points (a, b, c and d) in Fig. 3. Movies S1 and S2 correspond to the first band and band-gap of the metamaterial made of sub-wavelength hole arrays (points a and b in Fig. 3(a), respectively) with $d_z = 2.25$ mm, whereas movie S3 corresponds to the first band of the metamaterial made sub-wavelength hole arrays but with $d_z = 2.75$ mm (point c in Fig. 3(b)). Finally, movie S4 shows electric field propagation at the first band of the photonic crystal made of propagating hole arrays (point d in Fig. 3(d)). Notice that the structures are infinite in the “x” and “y” dimensions and only the unit cell is shown.

For the sub-wavelength structure with a longer longitudinal period, $d_z = 2.75$ mm, working in its first band, at 54.6 GHz (point c in Fig. 3(b), $\lambda = 5.49$ mm), it is readily seen (movie S3) that phase and group velocities travel parallel inside the structure, giving evidence of standard, right-handed behaviour.

For propagating holes working in its first band, at 53.5 GHz (point d in Fig. 3(c), $\lambda = 5.61$ mm), it is readily seen (movie S4) that phase and group velocities travel parallel inside the structure, giving again evidence of standard, right-handed behaviour.

Finally, the electric field evolution at the band-gap of sub-wavelength structure with a longer longitudinal period, $d_z = 2.75$ mm, and of the propagating hole structure are not given since they show a similar behaviour as that of movie S2.

5. Discussion

The physical mechanism underlying the EOT is a resonant coupling process through the surface electromagnetic modes formed on each metal-dielectric interface of the periodic structure [7]. An evanescent mode is excited inside the holes, which collaborate together to couple the power to the output face. Therefore, by drilling holes in a perfectly conducting material surface waves can be engineered and EOT achieved. Furthermore, as it is shown in this work, by periodically stacking subwavelength hole arrays not only EOT is achieved but a left-handed inner propagation can be created as well.

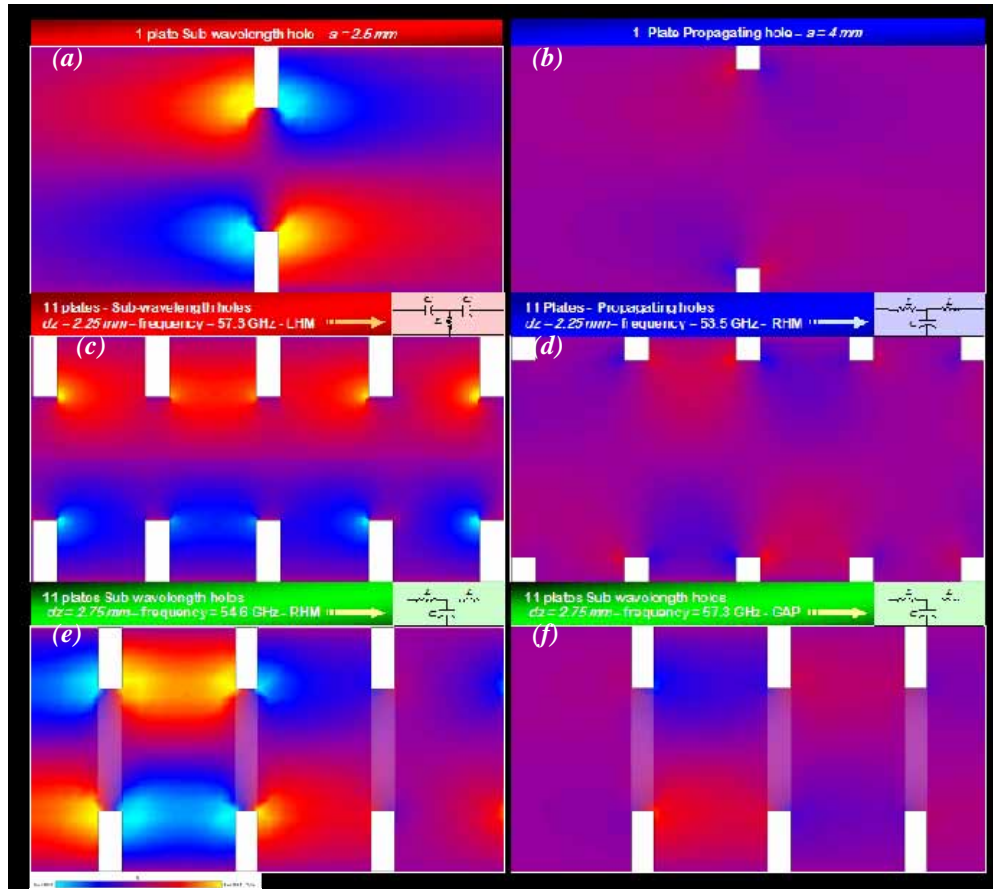


Fig. 5. Simulations for the cases of single sub-wavelength hole array structure (a) in the first band (EOT band) at 57.3 GHz. Single propagating hole array structure (b) at 53.5 GHz. Sub-wavelength hole array structure with 11 stacked plates spaced $d_z = 2.25$ mm (c) at 57.3 GHz. Propagating hole array structure with 11 stacked plates spaced $d_z = 2.25$ mm (d) at 53.5 GHz. Sub-wavelength hole array structure with 11 stacked plates spaced $d_z = 2.75$ mm (e) at 54.6 GHz and (f) inside the band gap at 57.3 GHz.

Since the times of radar development, it is well known that a sub-wavelength hole in a conducting plate can be considered as a self-inductive element, being the self-inductance larger as the hole diameter decreases and, conversely, a capacitive response is obtained when the hole diameter increases [31]. Therefore a subwavelength hole array in a conducting plate can be considered as an array of self-inductance elements. The hole array plate stacking brings about a mutual capacitance, C_{plates} , between the plates in such a way that an structure of shunt L_{hole} and series C_{plates} elements respectively is created. Additionally, the free space between the plates behaves as a transmission line with a distributed series inductance L_{line} and a distributed shunt capacitance C_{line} that permits wave propagation [32]. For a fixed periodicity within the plate plane, as the hole diameter decreases the fractional area of metal is enlarged and the capacitance C_{plates} between the plates increases. At the same time, C_{plates} is augmented as the plates are stacked closer.

A theoretical model of the phenomenon valid for normal incidence can be developed. This model is based on the introduction of an artificial waveguide with two ideal magnetic

conductor vertical planes and two ideal electric conductor horizontal planes in such a way that the diffraction problem is reduced to that waveguide containing the transversal unit cell inside. The physical behavior of the structure can be described by the modes of the artificial waveguide and their interaction in the longitudinal periodic structure. Due to the complex electromagnetic field distribution governing this problem, we will follow a simplified approach in order to identify the kind of propagating waves present in these structures. A thorough analysis of the electromagnetic fields' structure within the afore-mentioned model will be published elsewhere [33]. Here, we have considered the evolution of the z -component of the electric field (i.e. perpendicular to the plates) along the y - z cutting plane at the frequency where EOT and LHM occur. Fig. 5(a) and Fig. 5(b) show the field for a single plate of subwavelength and propagating hole arrays respectively. It is clear that the electric field for subwavelength holes is much more intense than for propagating ones at the edge of each hole. Moreover, the field out of the subwavelength hole array plate extends over a longer distance perpendicular to the plate. Figs. 5(c) to 5(f) show the electric field for different stacked structures: subwavelength hole array plates stacked with periodicities $d_z = 2.25$ mm in the EOT-LHM band (Fig. 5(c)) and $d_z = 2.75$ mm in the EOT-RHM band (Fig. 5(e)) and inside the bandgap (Fig. 5(f)), as well as propagating hole array plates stacked with periodicity $d_z = 2.25$ mm (Fig. 5(d)). From this figure it is clear that the electric field along z behaves similarly for all the cases of subwavelength or propagating stacked hole arrays (Figs. 5(d), 5(e), and 5(f)) where usual RHM wave propagation has been observed (note that a RHM EOT is also present in Fig. 5(e)). In these cases, the fields are not able to change the total series inductance and the total shunt capacitance and, therefore, the waves are propagating in the usual RHM way. This is also in agreement with the dispersion diagrams of Fig. 3.

However, for the case of EOT LHM, the field is very different compared with the remaining cases, see Fig. 5(c). It suggests that the inter-plate series C_{plates} and the subwavelength hole shunt inductance L_{holes} become dominant. Therefore, a dual transmission line [32], consisting of dominant shunt inductances and series capacitances, is formed. The key property of this simplified and idealized dual transmission line model is that it supports waves where energy and phase fronts are travelling in opposite ways, which implies that LHM propagation is present. It can be consequently stated that a left-handed metamaterial can be obtained by EOT through a photonic crystal structure of metallic plates with subwavelength hole arrays whenever the longitudinal periodicity of the structure is short enough to allow for an intense coupling between the subwavelength hole array plates. Conversely, a right-handed propagation is obtained for spaced subwavelength hole arrays and for arrays of propagating holes. Our results provide direct evidence to the previous statement that the extraordinary transmission, negative refraction, and photonic band-gap are connected phenomena.

EOT through subwavelength hole arrays was originally achieved in the visible range [5,6], and afterwards demonstrated in the millimetre and microwave regimes provided a minimal number of interacting holes is present [29,30]. Conversely, left-handed metamaterials have been already achieved for frequencies in the microwave range [16,17], being now the challenge to build left-handed metamaterials that work at visible frequencies. The scaling up of left-handed structures based on split ring resonators to the optical regime is far from trivial. Split-ring resonators with critical features controlled on the level of 10 nm should be built, which is technologically difficult to achieve. Furthermore, inherent losses appearing in the optical regime could limit the response of these elements. It would be interesting to demonstrate the possibility of engineering left-handed metamaterials at the THz and the visible ranges by means of stacked subwavelength hole arrays drilled in metallic plates or by using plasmonic materials with sufficiently negative real part of the permittivity. Here, the role of EOT phenomenon in sub-wavelength hole arrays is essential in order to have an important useful power level at the output of the device and to provide the necessary shunt inductance to cause left-handed propagation when the plates are close enough.

6. Conclusion

In this work we have shown how a left-handed metamaterial can be achieved by the periodic stacking of sub-wavelength hole array plates to form a photonic band-gap structure. Our results provide direct evidence that extraordinary transmission, negative refraction and photonic-band gap are connected phenomena. The reported results have been achieved for the millimetre range, but similar results are expected to happen at optical frequencies since extraordinary transmission has been shown at optical frequencies and the kind of structure presented here will present low losses in higher frequency regime. The control of the EOT-LHM could lead to a new class of practical devices both in the microwave and in the optical range. Further experiments and theoretical analysis are needed to grasp the full implications of these findings.

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